Superfluid density suppression and quasiparticle interaction in $Bi_2Sr_2Ca_{1-x}Pr_xCu_2O_{8+\delta}$ single crystals

2005 J. Phys.: Condens. Matter 17 689

(http://iopscience.iop.org/0953-8984/17/4/011)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **17** (2005) 689–695 doi:10.1088/0953-8984/17/4/011

Superfluid density suppression and quasiparticle interaction in $Bi_2Sr_2Ca_{1-x}Pr_xCu_2O_{8+\delta}$ single crystals

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Received 20 September 2004, in final form 20 December 2004
Published 14 January 2005
Online at stacks.iop.org/JPhysCM/17/689

Abstract
The Pr suppression of the superfluid density in $Bi_2Sr_2Ca_{1-x}Pr_xCu_2O_{8+\delta}$ single crystals is discussed using the zero-temperature in-plane penetration depth extracted from the second peak field in magnetization curves. It is found that the results fit better to the modified dirty d-wave model than the usual model. The relationship between the superfluid density and the critical temperature is also discussed in the underdoped region and one finds that the phase fluctuation model cannot account for the critical temperature in the system, which may be due to the interaction between the thermally excited quasiparticles and the impurity scattering induced quasiparticles.

1. Introduction

The dirty d-wave superconductor approach [1, 2] was regarded as a successful model to depict impurity or disorder scattering effects in high T_C superconductors. It suggested that the impurity or disorder gave rise to an impurity band of extended states near the Fermi level that dominated the low temperature behaviours and led to the linear temperature dependence of penetration depth changing to a T^2 dependence [1]. Many experiments have confirmed this crossover in the low temperature range [3–5]. However, some discrepancy between this model and experimental results has also been reported. For instance, contrasted to the predicted conductivity $\sigma \propto T^2$, experimental results exhibited a conductivity temperature variation $\sigma \propto T$ or even sublinear temperature dependence [6], and furthermore the impurity or disorder suppression of the superfluid density ρ_s at low temperature in the $YBa_2Cu_3O_{7-\delta}$ system was more rapid than predicted [7]. Recently, the dirty d-wave superconductor model was modified by taking consideration of the suppression of the order parameter around the position of the impurity or disorder [8]. The modified model can account for the low temperature $\sigma \propto T$ relationship and gives more rapid superfluid density suppression than the usual dirty d-wave approach, while the results for the temperature dependence of the penetration depth and other thermodynamic quantities change very little. In this paper, the Pr suppression of the superfluid density ρ_s in $Bi_2Sr_2Ca_{1-x}Pr_xCu_2O_{8+\delta}$ ($x = 0, 0.11, 0.17, 0.28$) single crystals is discussed by using the in-plane penetration depth extracted from the second peak field in the magnetization curves. It is found that the experimental results fit better with the modified model than the prototype model. The relationship between ρ_s and critical transition temperature T_C of the Pr doped Bi-2212 crystals in the underdoped region is also discussed. It is found that the precursor superconductivity scenario [9] cannot account for the experimental results in this system and the interaction between thermally excited and impurity induced quasiparticles may explain this discrepancy.

2. Experimental details

$Bi_2Sr_2Ca_{1-x}Pr_xCu_2O_{8+\delta}$ single crystals were grown using a self-flux method with excess Bi_2O_3 included to act as a flux. Details for crystal growth have been described elsewhere [10]. A typical dimension of the crystal was $3 \times 2 \times 0.03$ mm^3. The Pr content of the crystals was determined by energy-dispersive x-ray (EDS) analysis using a scanning microscopy (Stereoscan 440, Leica). The magnetization measurements were carried out with a commercial superconducting quantum interference device (SQUID) magnetometer (Quantum Design $MPMS_2$) down to 5 K in an applied field from 1 Oe to 10 kOe with field direction parallel to the c-axis of the crystal.

3. Results and discussion

The magnetization curves $M(H)$ for $Bi_2Sr_2Ca_{1-x}Pr_xCu_2O_{8+\delta}$ ($x = 0, 0.11, 0.17, 0.28$) single crystals were measured at different temperatures. A second peak in the magnetization curve appears in the temperature regions of 20–35, 20–30, 17.5–25, and 15–17.5 K for the crystals with $x = 0$, 0.11, 0.17, and 0.28, respectively. The results are consistent with other reports in the $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) system [11]. Recently, it was reported that the second peak appears in a much extended temperature range in heavily Pb doped Bi-2212 single crystals [12–14], and only in this system can it show the characteristic [14]. Figure 1 shows the magnetization curves of $Bi_2Sr_2Ca_{1-x}Pr_xCu_2O_{8+\delta}$ ($x = 0.17$) at several temperatures. It can be seen that the second peak field increases very weakly with decreasing temperature, which is consistent with other reports in the Bi-2212 system [15]. The magnetization curves of $Bi_2Sr_2Ca_{1-x}Pr_xCu_2O_{8+\delta}$ crystals at 25 K for $x = 0$, 0.11, and 0.17 and 17.5 K for $x = 0.28$ are shown in figure 2. It is found that the second peak field decreased dramatically with increasing of Pr content x, which reveals that the interlayer coupling is weakened by Pr doping in the system [16].

Many explanations have been put forward to depict the mechanism of the second magnetization peak in the Bi-2212 system [17–22]. The origin of the second peak was generally explained as the dimensional crossover from 3D vortex lines to 2D pancake vortices [20–22], and this picture was supported by many experimental observations [11, 23, 24]. Because the Josephson length $\lambda_J = \gamma s$ (here γ is the anisotropic parameter of the material and s is the interlayer distance) is bigger than the zero-temperature in-plane penetration depth $\lambda_{ab}(0)$, the magnetic coupling dominates the pancake interaction in different layers in the Bi-2212 system [25–27] (except the heavily Pb doped Bi-2212 system). The crossover field from 3D

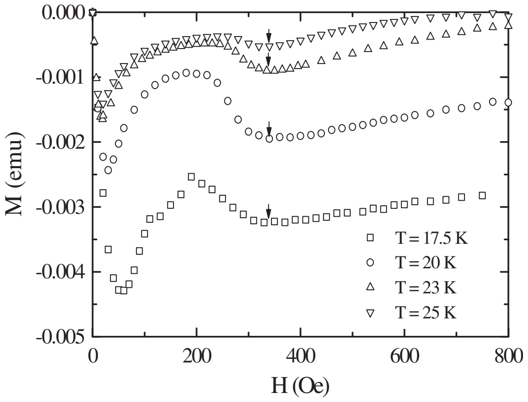

Figure 1. Magnetization curves $M(H)$ for the $Bi_2Sr_2Ca_{0.83}Pr_{0.17}Cu_2O_{8+\delta}$ single crystal at different temperatures. The second peak for each curve was indicated by arrows.

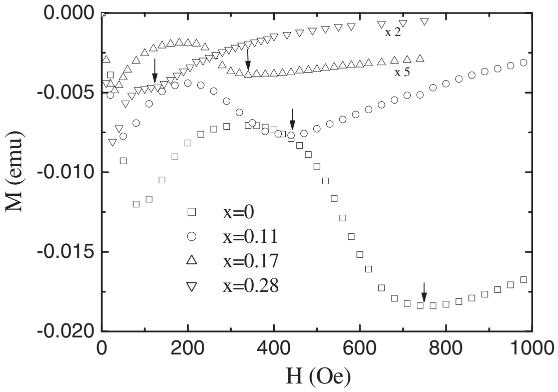

Figure 2. Magnetization curves $M(H)$ for $Bi_2Sr_2Ca_{1-x}Pr_xCu_2O_{8+\delta}$ single crystals at 25 K for $x = 0$, 0.11, and 0.17 and at 17.5 K for $x = 0.28$. The second peak for each crystal is indicated by arrows.

vortex lines to 2D pancake vortices can be expressed as [25–27]

$$B_{\mathrm{cr}} \cong \frac{\Phi_0}{\lambda_{ab}^2(0)}, \tag{1}$$

where Φ_0 is the magnetic flux quantum. Equation (1) is used to extract the zero-temperature in-plane penetration depth $\lambda_{ab}(0)$ for different Pr doped materials from the second peak fields shown in figure 2. It is obtained that $\lambda_{ab}(0) = 1670$ Å for the $x = 0$ crystal, which is consistent with the other reported in-plane penetration depth data in very clean Bi-2212 crystals [28].

Some data transformation must be done before one can compare the experimental results with theoretical predictions. The normalized superfluid density ρ_{s} for different Pr doped Bi-2212 single crystals is obtained by using $\rho_{\mathrm{s}}(0)_x/\rho_{\mathrm{s}}(0) \approx \lambda_{ab}^2(0)_{x=0}/\lambda_{ab}^2(0)_x$, where $\lambda_{ab}(0)_{x=0}$ and $\lambda_{ab}(0)_x$ are the zero-temperature in-plane penetration depth in pure and Pr doped superconductors, respectively, and the variation of the effective mass of the superconducting carrier with Pr doping content is neglected. It was found that the superconductivity is suppressed completely in Pr doped Bi-2212 crystals when x reaches the critical doping content $x_{\mathrm{c}} = 0.6$ [29]. The normalized impurity scattering rate parameter $\Gamma/\Gamma_{\mathrm{c}}$ is obtained using

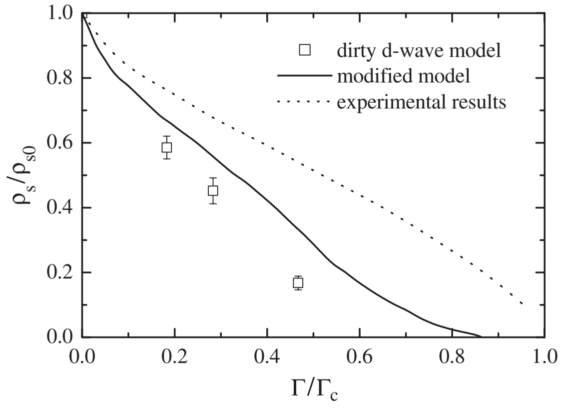

Figure 3. Comparison of the superfluid density ρ_s versus Γ of $Bi_2Sr_2Ca_{1-x}Pr_xCu_2O_{8+\delta}$ single crystals with dirty d-wave superconductor models. The solid and dashed curves are the results of the dirty d-wave model with and without order parameter scattering, respectively.

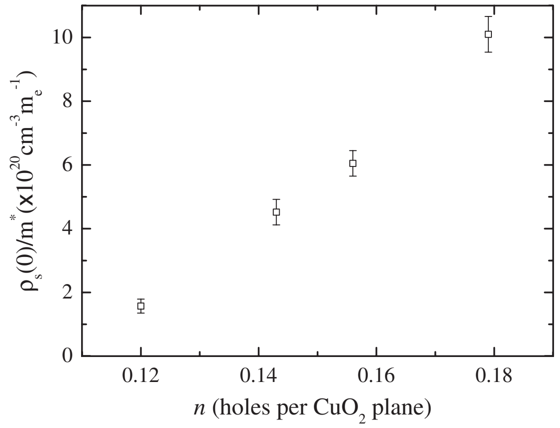

Figure 4. Hole density dependence of $\rho_s(0)/m^*$ for the Pr doped Bi-2212 system.

$\Gamma/\Gamma_c \approx x/x_c$; here the changes of the density of states with doping content are neglected. The experimentally obtained superfluid density ρ_s versus Γ is shown in figure 3 as open squares. Compared with theoretical results, it can be seen that Pr suppression of the superfluid density fits better with the modified dirty d-wave model than the prototype model. Note that in the theoretical treatment the carrier density in the normal state keeps constant with increasing density of strong scattering centres in the superconductors. However, the holes per copper site, n versus x, were experimentally obtained as $n = 0.179 - 0.21x$ in Pr doped Bi-2212 crystals [29], which would cause more severe suppression of superfluid density in experiment. Furthermore, the suppression of the order parameter should give lower Γ_c than without order parameter suppression. Thus the obtained more rapid suppression of ρ_s in the experiment than in the modified dirty d-wave model is reasonable.

Figure 4 shows the hole density n dependence of $\rho_s(0)/m^*$ in Pr doped Bi2212 crystals. It is found that $\rho_s(0)/m^*$ decreases rapidly with decreasing n in this system. The approximately linear relationship of $\rho_s(0)/m^*$ with n in the $n < 0.19$ regime is consistent with that obtained in Y123 and Tl1212 systems [30] and many other superconducting systems [31–33] by the muon-spin-relaxation or the ac susceptibility measurements.

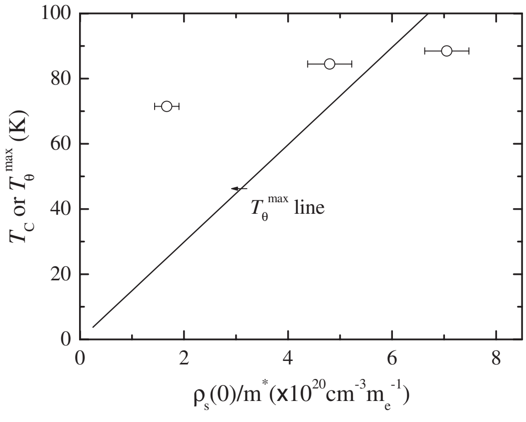

Figure 5. Critical temperature T_C and T_θ^{max} as a function of $\rho_s(0)/m^*$ in the Pr doped Bi-2212 system. The T_C for the underdoped samples lies far to the left of the T_θ^{max} line.

Now we turn to discuss the relationship between the superfluid density $\rho_s(0)/m^*$ and superconducting critical transition temperature T_C. In underdoped cuprate superconductors, Emery and Kivelson [9] proposed that the phase fluctuation led to the destruction of long-range superconducting order in the materials. They defined T_θ^{max} as a temperature at which long range ordering disappears, namely

$$T_\theta^{max} = A\frac{a}{16\pi k_B}\left(\frac{\hbar c}{e\lambda(0)}\right)^2. \tag{2}$$

Here k_B is the Boltzmann constant, c the velocity of light in vacuum, $\hbar$ the Planck constant, e the electron charge, $\lambda(0)$ the zero-temperature penetration depth, parameter A is determined by interlayer coupling strength and $A \approx 0.9$ for all layered cuprate superconductors and parameter $a = 7.5$ Å for the Bi-2212 system [9]. When $T > T_\theta^{max}$, the superconductor is in the normal state with short range pairing correlation remaining. T_θ^{max} gives an upper limitation of T_C in the underdoped region.

In the Pr doped Bi-2212 crystals, the $x = 0.11$ sample is approximately optimally doped, and the $x = 0.17$ and 0.28 samples are in the underdoped region in our experimental conditions. Inserting the obtained $\lambda_{ab}(0)_x$ into equation (2), one finds T_θ^{max} equals 69 and 27 K for $x = 0.17$ and 0.28 samples, respectively, which are smaller than the measured critical temperature T_C of the corresponding sample ($T_C = 84$ K for $x = 0.17$ and $T_C = 71$ K for $x = 0.28$ [29]). For the $x = 0.17$ sample, one may argue that the lower T_θ^{max} compared with T_C could be resolved if a little larger A were used. For the $x = 0.28$ sample, however, if the largest A (2.2 for an isotropic 3D materials [9]) is used, the obtained T_θ^{max} (66 K) is still smaller than the measured T_C. Figure 5 shows the comparison of measured T_C in Pr doped Bi-2212 crystals with T_θ^{max} line in the underdoped region. It is found that T_C lies far to the left of the T_θ^{max} line, which is consistent with the results in the underdoped Zn substituted $Y_{0.8}Ca_{0.2}Ba_2Cu_{3-x}Zn_xO_{7-\delta}$ (Y, Ca-123) system [34]. So one can conclude that the precursor superconductivity scenario [9] as well as the Uemura relationship [35] cannot account for the critical temperature T_C in the Pr doped Bi-2212 system.

This discrepancy between the precursor superconductivity scenario [9] and experiment results in the Pr doped Bi-2212 system has no relation to the phase separation in the Bi-2212 system [33]. We give a possible reason that may account for this discrepancy. It was well established that, in the dirty cuprate superconductors, strong scattering impurities, such as Zn substitution for Cu or Pr substitution for Ca in the Bi-2212 system, can induce quasiparticles around them [36, 37], which leads to the rapid reduction of the zero-temperature superfluid density $\rho_s(0)$; see the solid curve in figure 3. These impurity-induced quasiparticles should have some influence on the thermal quasiparticle excitation process. We suggest that the quasiparticles excited by impurity scattering may occupy the lower energy levels and obstruct the thermal excitation of quasiparticles. In fact, the $\rho_s(T)$ decreases more slowly with increasing temperature in the dirty cuprates than in the clean cuprates in the very low temperature region [1]. As suggested by Lee and Wen [38], the quasiparticle excitation is an effective way of destroying the superconducting state by driving ρ_s to zero. In the clean superconductors, the temperature dependence of ρ_s due to thermal excitation is given as [38]

$$\frac{\rho_s(T)}{m^*} = \frac{\rho_s(0)}{m^*} - \alpha T, \tag{3}$$

where m^* is the effective mass of the superconducting carriers and α is a parameter related to the zero-temperature energy gap magnitude. It was obtained that $T_C = \rho_s(0)/m^*\alpha$. If we simply assume that this relation could be used in the Pr doped Bi-2212 system and the Pr doping decreases α as well as $\rho_s(0)$, a relatively large T_C can also be obtained from equation (3). However, the linear temperature dependence of $\rho_s(T)$ is not applicable to the dirty superconductors quantitatively; a more accurate equation can be obtained from the dirty d-wave superconductor model [1, 2]. In dirty cuprates, the penetration depth $\lambda(T)$ shows T^2 dependence in the low temperature region [2] ($T \ll T_C$); the temperature dependence of superfluid density $\rho_s(T)$ could be expressed as

$$\frac{\rho_s(T)}{m^*} \cong \frac{\rho_s(0)}{m^*}\left(1 - \frac{\pi\lambda_{ab}(0)_{x=0}/\lambda_{ab}(0)_x}{3\beta\Delta_0}T^2\right); \tag{4}$$

here β is the scattering related constant and Δ_0 is the zero-temperature energy gap magnitude. The coefficient of T^2 decreases with increasing impurity content since $\lambda_{ab}(0)_x$ and β increase with increasing impurity content and Δ_0 increases with decreasing hole density n [39]. In dirty d-wave superconductors, though the zero-temperature superfluid density may be exhausted greatly by impurity scattering, it is partly compensated by the low $\rho_s(T)$ decrease rate, i.e. low thermal quasiparticle excitation rate, with increasing temperature, which may account for the experimentally observed rather large T_C in heavily impurity doped cuprates. Thus we would like to attribute the rather lower excitation rate of the thermal quasiparticle in dirty cuprates to the interaction between the impurity induced quasiparticles and the thermally excited quasiparticles rather than the other interpretations.

It is noted that the strong interaction in thermal quasiparticles has been proposed by analysing the angular resolved photoemission (ARPES) data in the Bi-2212 system [40] and the lower temperature penetration depth and heat capacity data in $La_{2-x}Sr_xCuO_4$ and $YBa_2Cu_3O_{6+x}$ systems [41]. Our experimental results may imply that there is an interaction between the thermal quasiparticles and impurity induced quasiparticles and this interaction changes the excitation behaviour of the thermal quasiparticles.

4. Conclusions

The zero-temperature in-plane penetration depth $\lambda_{ab}(0)$ of the Pr doped Bi-2212 single crystals is extracted from the second peak field in magnetization curves. The suppression of superfluid density $\rho_s(0)$ by Pr is more consistent with the modified dirty d-wave model with order parameter scattering than that without order parameter scattering. The precursor superconductivity scenario predicts lower critical temperature than that measured in the underdoped Pr doped Bi-2212 system and this discrepancy may be due to the interaction between the quasiparticles induced by impurity scattering and thermal excitation.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Nos 60490290 and 90306015) and the Ministry of Science and Technology of China (NKBRSF-G19990646). SJF thanks the Foundation for Talented Teachers of Anhui University for partial support.

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